S282 Astronomy

Jets and black holes

Study time: 40 minutes

Summary

This activity relates to a video sequence in which you will consider astrophysical jets. Jets were discovered in connection with active galaxies, but are now recognized to occur on a wide range of scales. The sequence concentrates on the observational techniques that are used to study this energetic phenomenon, and considers the link between jets and black holes. You should have completed Chapter 3 of *An Introduction to Galaxies and Cosmology* before starting this activity.

Learning outcomes

- Appreciate the way that radio and millimetre-wave telescopes are used to investigate jets and associated structures in a wide variety of astronomical objects.
- Recognize that jets occur in a variety of astrophysical objects.

The activity

This programme brings together a discussion of the outflow from star-formation regions (mentioned in Chapter 5 of *An Introduction to the Sun and Stars*), jets from evolved stars, and the jets associated with active galaxies (the subject of Chapter 3 of *An Introduction to Galaxies and Cosmology*). The observing techniques featured are those of radio astronomy, particularly radio interferometry.

The activity is based around a long (about 24 minute) video sequence which was originally broadcast as a television programme in 1997. Although there have been some advances in observing technology since the video was made, the principles behind the observations are still relevant today. Furthermore, the mechanism of astrophysical jet formation remains a mystery.

- Start the S282 Multimedia guide and then click on Jets and black holes under the 'Galaxies' folder in the left-hand panel.
- Press the Start button to run the video sequence.

After you have watched the video sequence, read the summary provided in the 'Notes' below.

Notes

In some stars and galaxies we observe an interesting and important phenomenon – jets of material streaming out of these bodies. In many cases these jets can only be observed at long wavelengths, and require observations made with higher spatial resolution than is normally available with a ground-based optical telescope. Until we understand them (and we are far from doing so) our knowledge of stellar and galactic evolution will remain partial and precarious. This video sequence addressed these points, in four sections.

1 Young stars are observed in dense clouds, which are assumed to be contracting under self-gravitation, though this process is never directly observed. A common feature of such star-forming regions is *expulsion* of matter in symmetrical (back to back) jets which are known as bipolar outflows (*An Introduction to the Sun and Stars* Section 5.3.4). They are typically about a parsec long (similar to the distance from us to Alpha Centauri) and carry away matter at about $10^{-6}M_0$ a year, so they must obviously be short-lived. We saw how the James Clerk Maxwell Telescope (JCMT), operating at millimetre and submillimetre wavelengths is able to make detailed images of such objects. By also recording spectra one can find how the Doppler shift of a strong spectral line (a rotational transition of the carbon monoxide molecule in the case shown) varies across the object: the speed and collimation of the outflow is clearly revealed.

   Many such bipolar outflows have been seen (see, for example, *An Introduction to the Sun and Stars* Figure 5.13) and they are compatible with the idealized visualization shown in *An Introduction to the Sun and Stars* Figure 5.12. Notice the presence of a disc or torus at the centre (which would be called an accretion disc in other contexts).

   There is only a hint of it in the JCMT image shown in the programme, but such discs are thought to be associated with all types of jet. The nature of the driving force is unknown.

2 The next step in the story is the star SS 433 at the centre of a nearby supernova shell W50 – a star now identified as a spinning and wobbling compact star, which accretes material from a binary partner, presumably into an equatorial disc (see the illustration of a similar type of binary system in *An Introduction to the Sun and Stars* Figure 9.15), and somehow directs it into fierce *axial* jets. This description is almost identical with that of bipolar outflow, but the length of the jets in SS 433 is much larger – extending some 50 pc from the central object into the surrounding interstellar medium.

These jets, and their precession, were first identified from optical spectra that had the extraordinary feature of containing both red-shifted and blue-shifted emission lines. The shifts varied with a period equal to the precessional period. Radio imaging at very high (milli-arcsec) resolution revealed the very innermost section of the jets, where the radio emission comes from blobs rather than the whole jet. This enabled a direct measurement of transverse jet speed, to compare with the Doppler shifts due to radial speed (with respect to us). Both give speeds in the region of a quarter that of light! The jets as revealed by the visible light images, and the radio lobes, are vastly bigger than the innermost section shown in the high-resolution radio image sequence. As in the case of bipolar outflows, both the source of the power, (much greater in this case), and the very effective collimation mechanism, are still mysteries. The SS 433 jets are enormously long in comparison with the tiny compact star, which is thought to be a neutron star and therefore only a few kilometres in diameter.

SS 433 is one of several binary stellar systems in our Galaxy that have jets. Because these relatively close objects can be studied in detail they may reveal processes common in many other types of accretion phenomenon.

3 Whatever the mechanism operating in SS 433, something similar seems to apply at the much bigger scale of the cores of active galaxies. In studying distant galactic centres astronomers benefit greatly from the very high resolution afforded by arrays of radio dishes. One such array, MERLIN (the Multi Element Radio Linked Interferometric Network), has seven dishes spread over England, directly linked to the Jodrell Bank Observatory. The video sequence showed the characteristic period variation of the *interference* of signals from a pair of dishes as the Earth rotates the baseline relative to the source. We saw a simulation (made at the VLA (Very Large Array) by Rick Perley) of the way the signals of many pairs can be correlated to reveal fine structure in the source object. You saw a typical double radio source (a twin-jet), Cygnus A, as an example (see *An Introduction to Galaxies and Cosmology* Figure 3.20). A refinement of this technique, using very precise local timing and subsequent correlation rather than direct real-time links, allows the use of very long (intercontinental) baselines. (That's how high resolution images of the moving blobs in SS 433 were obtained.) This is called *very long baseline interferometry* (VLBI).

It has been known for a long time that many galaxies have violent activity in a compact core – an active galactic nucleus. This shows itself in a variety of ways, but many astronomers think that these represent much the same sort of structure seen from different angles, rather than a multiplicity of different structures and mechanisms. The hypothetical 'unified model' consists of a torus of matter leaking into a tiny accretion disc, which is heated to X-ray energies as it spirals into a very massive black hole, of mass equivalent to perhaps a hundred million stars (see *An Introduction to Galaxies and Cosmology* Figure 3.32).

In this model, an axial *pair* of jets emerges from a region close to the black hole. The mechanism by which material is accelerated into jets is not well understood. As described in Chapter 3 of *An Introduction to Galaxies and Cosmology*, the physical mechanisms that may play a role in jet formation are the magnetic fields in the accretion disc and radiation pressure effects close to the black hole.

In fact *only one* jet is normally observed. It is thought that the advancing jet – the jet that is heading in roughly our direction – is visible because it is greatly brightened due the process of relativistic beaming. Mostly, the jets are not particularly long in galactic terms – say a few times the thickness of the galaxy – hence the need for high-resolution imaging. There are several hypotheses for the guiding mechanism for the jet, and for the method by which electron energy is replenished along the jet, so that the electrons sustain the synchrotron radio emission.

4 In those jets which are *very* long there must be some mechanism that constricts and guides the outflowing material. Such jets may be hundreds of kiloparsecs or even megaparsecs long. They end in clouds of radio emission often called lobes, as we saw in the case of Cygnus A. Sometimes the jets are strongly curved, perhaps by interaction with an intergalactic medium, or by movement of the source during the millions of years of its existence. Martin Rees summarized the great advance that is waiting to be made when the processes occurring in jets can be explained.

Video credits

Presenter – Barrie W. Jones (Open University)

Speakers (in order of appearance)

Ian Robson (JCMT Hawaii, and University of Central Lancashire)

Peter Wilkinson (NRAL, University of Manchester)

Rick Perley (Very Large Array, New Mexico)

Meg Urry (Space Telescope Science Institute, Baltimore)

Andrew Wilson (Space Telescope Science Institute, Baltimore)

Duccio Macchetto (Space Telescope Science Institute, Baltimore)

Martin Rees (University of Cambridge)

Producers – Tony Jolly (BBC) and Cameron Balbirnie (BBC)

Course Team consultants – Alan Cooper, David Clark (SERC), Barrie W. Jones